BRUSHLESS PERMANENT MAGNET MOTOR WITH HIGH POWER DENSITY, LOW COGGING AND LOW VIBRATION

FIELD OF THE INVENTION

[0001] The present invention relates to electric machines, and more particularly to brushless permanent magnet (BPM) electric machines with low cogging torque, high power density and low vibration.

BACKGROUND OF THE INVENTION

[0002] Electric machines, such as motors and generators, typically include a stator that is mounted inside a housing and a rotor that is supported for rotation relative to the stator. Electric machines are often integrated into devices such as appliances. The size and/or capacity of the device incorporating the electric machine may be an important factor in the purchasing decision. The size and power of the electric machine also has a significant impact on the overall size and capacity, respectively, of the device.

[0003] The power density of an electric machine is defined as the ratio of the power output and the volume of electric machine. A relatively high power density (e.g., high power output relative to volume) is usually desirable. The high power density allows the electric machine to have either a smaller overall size for a given power output or a higher output for a given size.

[0004] When the electric machine rotates during operation, the electric machine vibrates, which produces noise. The noise level of the electric machine may be an important factor in the buying decision. Therefore, it is desirable to

decrease vibration, which reduces noise. Conventional approaches for reducing vibration tend to decrease power density as well. In other words, reduced vibration and noise has been achieved at the cost of reduced power output and/or increased volume.

SUMMARY OF THE INVENTION

[0005] Accordingly, the present invention provides a brushless permanent magnet electric machine having a stator assembly including a stator core that defines (12 x n) slots and stator teeth having a generally "T"-shaped cross section. Winding wire is wound around the stator teeth, wherein a radially outer edge of the stator teeth define a crowned surface. A rotor includes permanent magnets defining $(12 \pm 2)n$ poles, wherein n is an integer greater than zero.

[0006] In one feature, the stator core is located inside of the rotor.

[0007] In another feature, the stator core is formed by a plurality of stacked stator laminations.

[0008] In another feature, a first radius of the crowned surface is less than a second radius defined by a circle that is tangent to a radially outermost point of the crowned surface of the stator teeth.

[0009] In still another feature, a slot opening is an angle between circumferential facing edges of adjacent stator teeth and tooth pitch is an angle between centers of adjacent stator teeth, wherein the slot opening is within a range of 10% to 20% of the tooth pitch.

[0010] In yet another feature, a first air gap between an end of the crowned surface and the permanent magnets is within a range of 1.25 to 2.00 times a second air gap between a center of the crowned surface and the permanent magnets.

[0011] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0013] Figure 1 is a schematic illustration of a device including a rotating member that is driven by a brushless permanent magnet (BPM) electric machine according to the present invention;

[0014] Figure 2 is a plan view of a stator lamination of the (BPM) electric machine according to the present invention;

[0015] Figure 3 is an enlarged plan view of a portion of the stator lamination of Figure 2;

[0016] Figure 4 is a cross-sectional view of a rotor of the BPM electric machine;

[0017] Figure 5A is an exemplary stator winding diagram for a first phase of a stator assembly according to the present invention;

[0018] Figure 5B is an exemplary stator winding diagram for a second phase of the stator assembly according to the present invention;

[0019] Figure 5C is an exemplary stator winding diagram for a third phase of the stator assembly according to the present invention;

[0020] Figure 6 is a graph comparing vibration characteristics of conventional electric machines to the electric machine according to the present invention;

[0021] Figure 7 is a more detailed view of the graph of Figure 6 illustrating a peak to peak distance of the vibration characteristics of the conventional electric machine; and

[0022] Figure 8 is a more detailed section of the graph of Figure 6 illustrating a peak to peak distance of the vibration characteristics of the electric machine according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0023] The following description of the preferred embodiments is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify similar elements.

[0024] Referring now to Figure 1, a device 10 is shown that includes a rotating member 12 that is driven by a brushless, permanent magnet (BPM)

electric machine 14. An exemplary device 10 is a washing machine where the rotating member 12 is a tumbler. The rotating member 12 is rotatably supported within a cavity 16 defined by a housing 18. A shaft 20 couples the rotating member 12 to the electric machine 14. The shaft 20 is rotatably supported by bearings 22 and includes a first end coupled to the rotating member 12 by a coupling 24. A second end of the shaft 20 is coupled to the electric machine 14.

[0025] The electric machine 14 is an inside-out, brushless permanent magnet (BPM) electric machine and is supported within a machine cavity 26 of the housing 18. The electric machine 14 includes an internal stator assembly 28 and an external rotor assembly 30. The internal stator assembly 28 is fixed to a mounting bracket 27 by supports 29. An air gap 31 is formed between the internal stator assembly and the mounting bracket 27. The external rotor assembly 30 is coupled to the rotating member 12 by the shaft 20. The external rotor assembly 30 is drum shaped and defines a donut-shaped cavity 32 within which the internal stator assembly 28 is disposed. Permanent magnets 34 are mounted to an internal surface of the external rotor assembly 30 and preferably include two or three magnetic poles per magnet. The internal stator assembly 28 includes windings 36 that are wound around one or more of the stator teeth. Electric current that flows through the windings 36 generates a rotating magnetic field that interacts with the magnetic poles of the permanent magnets 34 to rotate the external rotor assembly 30 relative to the stator assembly 28.

[0026] Referring now to Figures 1, 2 and 3, the internal stator assembly 28 includes a plurality of stator laminations 40 that are stacked together to form a

stator. Each stator lamination 40 defines a plurality of slots 42 that are located between generally "T" shaped stator teeth 44. The slots 42 include a slot opening formed between the teeth 44. Tooth pitch is defined as the angle between corresponding faces of two adjacent teeth 44 as illustrated in Figure 3. The angle of the slot opening between the teeth 44 is preferably within a range of 10% to 20% of the tooth pitch. The exemplary internal stator assembly of Figures 2 and 3 includes 24 slots. A series of bores 48 are provided to enable passage of fasteners (not shown) for attaching the stator to the housing 18.

[0027] As best seen in Figure 3, radially outer faces 46 of the stator teeth 44 are crowned and define a radius (x) that is less than a radius (y) of the stator laminations. More particularly, the radius y defines the distance from the tips of the stator teeth 44 to the center of the stator lamination. The radius x defines the crown arc of the outer faces 46 of the stator teeth 44. An air gap (A) (see Figure 1) is defined between the internal stator assembly 28 and the permanent magnets 34 of the external rotor assembly 30. The crown is formed such that air gaps (B) at the ends of the crowned face 46 are preferably 1.25 to 2.00 times the size of the air gap (A) (see Figure 3).

[0028] Referring now to Figures 1 and 4, a cross-sectional view of the rotor assembly 30 is shown. The rotor assembly 30 of Figures 1 and 4 is exemplary in nature and includes 10 permanent magnets 34. The number of permanent magnets 34 can vary according to the present invention as discussed further below.

[0029] The stator laminations 40 each define (12 x n) slots 42 and are wound to correspond to (12 $\pm$ 2)n magnetic poles. The value n is an integer that is greater than zero (i.e., n = 1, 2, 3, 4, ...). Exemplary slot and pole combinations defined by the stator laminations 40 can include 12 slots with 10 poles, 12 slots with 14 poles, 24 slots with 20 poles, 24 slots with 28 poles, 36 slots with 30 poles, 36 slots with 42 poles, etc. For example, the stator assembly 28, described in detail above, includes 24 slots and the rotor assembly 30 includes 20 poles (i.e., 10 permanent magnets having two poles each).

[0030] Referring now to Figures 5A, 5B and 5C, exemplary stator winding diagrams are shown for phases A, B and C, respectively of the 24 slot, 20 pole electric machine (i.e., n = 2 with (12 – 2)n poles) according to the present invention. As discussed above with reference to Figures 2, 3 and 4, the exemplary internal stator assembly 28 includes 24 slots and 24 teeth and the exemplary rotor assembly 30 includes 20 poles (10 permanent magnets). The phase windings 36, however, are wound to correspond to the alternating poles of the rotor assembly 30.

[0031] The phase A windings are wound across teeth T1 and T2, T7 and T8, T13 and T14, and T19 and T20 as shown in Figure 5A. The phase B windings are wound across teeth T9 and T10, T15 and T16, T21 and T22, and T3 and T4 as shown in Figure 5B. The phase C windings are wound across teeth T17 and T18, T23 and T24, T5 and T6, and T11 and T12 as shown in Figure 5C.

[0032] The combination of (12 x n) slots and (12 $\pm$ 2)n poles with crowned pole end faces reduces cogging and vibration. As a result, the noise of the electric machine is also reduced. Referring now to Figures 6 through 8, a vibration comparison is provided between a conventional electric machine and an electric machine according to the present invention. As can be seen, the conventional machine induces vibration at higher frequency and with a higher amplitude. More specifically, the largest peak to peak value is approximately 0.180g's and the smallest peak to peak value is approximately 0.070g's (see Figure 7). The electric machine according to the present invention induces vibration at a lower frequency and with significantly lower amplitude than the conventional electric machine. More specifically, the largest peak to peak value is approximately 0.040g's which is a 78% reduction. The smallest peak to peak value is approximately 0.020g's (see Figure 8) which is a 71% reduction.

[0033] The reduced vibration and noise generation is achieved with a relatively high power density. The power density is defined as a ratio between the power output and the volume of the electric machine. Table 4, below, provides a comparison between the conventional electric machine and the electric machine according to the present invention.

	Conventional	Present
Stator		
Stack (in)	1.278	1.250
Outside Diameter (in)	10.430	9.680
Slots	36	36
Bore (in)	5.00	5.00
Slot Fill	46%	42%
Rotor		
Outside Diameter (in)	11.14	10.5
Air Gap (in)	0.043	0.040

Magnet Poles	48	30
Magnet Material	Ferrite	Ferrite
Material Volume (in^3)	487	432

Table 4

While the power output of the machines is equivalent, the volume of the machine according to the present invention is approximately 11% lower. Thus, the power density of the electric machine according to the present invention is approximately 12.6% higher than that of the conventional electric machines.

[0034] Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the present invention can be implemented in a variety of forms. Therefore, while this invention has been described in connection with particular examples thereof, the true scope of the invention should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification and the following claims.